

The K-band Hubble diagram for the brightest cluster galaxies: a test for galaxy formation and evolution models

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Abstract. The K -band Hubble diagram for a sample of brightest cluster galaxies (BCGs) in the redshift range $0 < z < 1$ shows a very small scatter (0.3 magnitudes *r.m.s.*). The BCGs exhibit very little luminosity evolution in this redshift range: if $q_0 = 0.0$ we detect *no* luminosity evolution; for $q_0 = 0.5$ we measure a small *negative* evolution. If the mass in stars of these galaxies had remained constant over this period of time, substantial positive luminosity evolution would be expected: BCGs should have been *brighter* in the past since their stars were younger. This suggests that the stellar mass of the BCGs has been assembled over time through merging and accretion. We estimate that the stellar mass in a typical BCG has grown by a factor $\simeq 2$ since $z \simeq 1$ if $q_0 = 0.0$ or by factor $\simeq 4$ if $q_0 = 0.5$. These results are in remarkably good agreement with the predictions of semi-analytic models of galaxy formation and evolution set in the context of a hierarchical scenario for structure formation.

1. Introduction

Brightest cluster galaxies (BCGs) have been extensively studied at optical wavelengths (see, e.g., Lauer & Postman 1992; Postman & Lauer 1995 and references therein). The small scatter in their absolute magnitudes and their high luminosities make them useful standard candles for classical cosmological tests involving the Hubble diagram, such as the determination of q_0 and the variation of H_0 with redshift. However, there is now firm evidence that significant evolution has taken place in the colours and optical luminosities of cluster early-type galaxies (including the BCGs) since $z \simeq 1$. Thus the Hubble diagram could be seriously affected by evolutionary changes. The study of the BCGs in the near-infrared K -band (2.2μ) has two main advantages over optical studies: first, the k -corrections are appreciably smaller (indeed, they are negative) and virtually independent of the spectral type of the galaxies; and second, the light at long wavelengths is dominated by long-lived stars (see, e.g., Aragón-Salamanca et al. 1993). Thus the K -band luminosity is a good measure of the total stellar mass in the galaxies. In this paper we present new results on the K -band Hubble diagram for the BCGs and compare them with the predictions of semianalytic models of galaxy formation and evolution. A full account of these results is given in Aragón-Salamanca, Baugh & Kauffmann (1997).

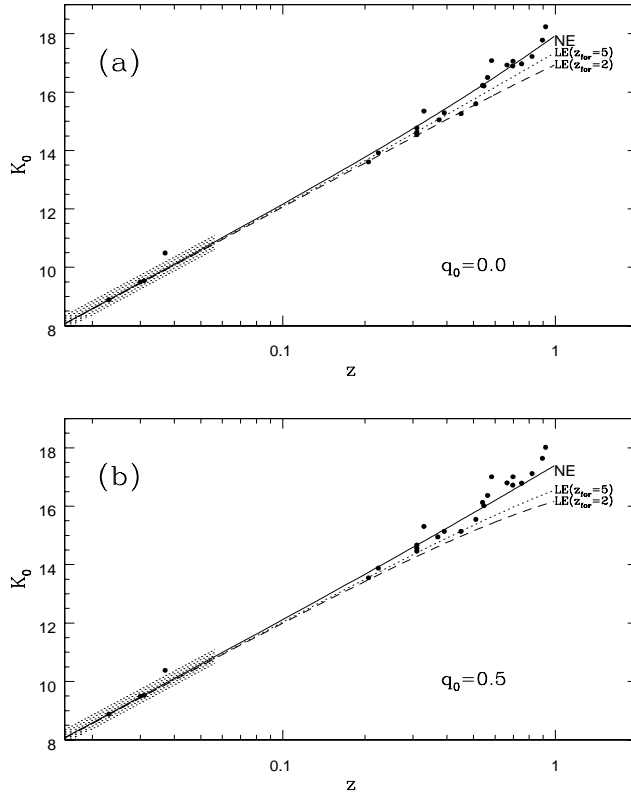


Figure 1. **(a)** Magnitude-redshift relation (Hubble diagram) for the Brightest Cluster Galaxies in the rest-frame K -band. The solid line shows the no-evolution prediction (which only takes into account the distance modulus) normalised to the low-redshift data. The dashed line corresponds to the luminosity evolution expected for a stellar population formed at $z_{\text{for}} = 2$ evolving passively. The dotted line shows the evolution expected for $z_{\text{for}} = 5$. The shaded area at low-redshift represents the K -band magnitudes of $z < 0.06$ BCGs estimated from the R -band data of Postman & Lauer. **(b)** As (a) but for $q_0 = 0.5$.

2. Observational results

We analyse a sample BCGs in optically-selected clusters ($0 < z < 1$) which should represent the richest clusters present at each redshift. The K -band data come from Aragón-Salamanca et al. (1993), Barger et al. (1996) and Barger (1997). Morphological information is available from ground-based and HST images for many of the clusters. In general, the BCGs are either cD galaxies or giant ellipticals. Photometry for the BCGs was obtained inside a fixed metric aperture of 50 kpc diameter ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ assumed throughout). Galactic reddening corrections, seeing corrections and k -corrections were applied as in Aragón-Salamanca et al. (1993).

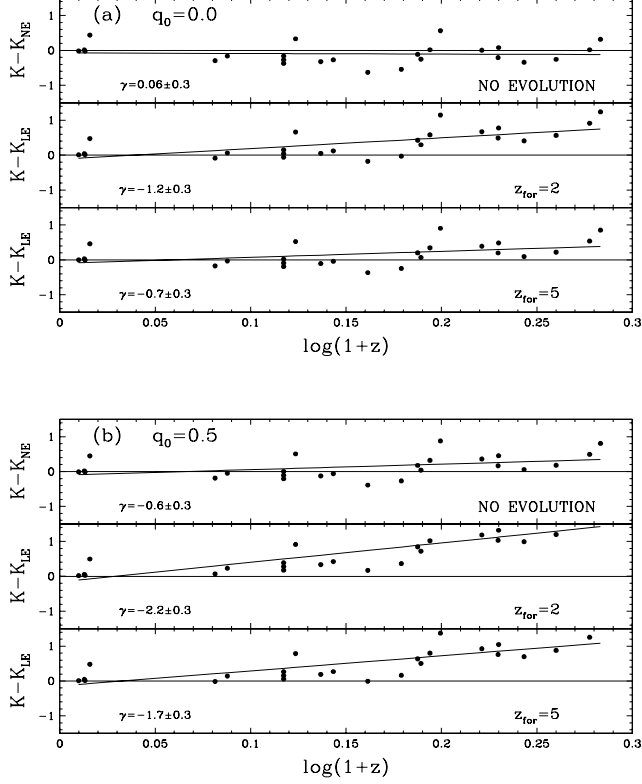


Figure 2. **(a)** Top panel: The same data presented in figure 1 after subtracting the no-evolution prediction. Middle and bottom panels: the same data after subtracting models for luminosity evolution in which the BCG stars form at $z_{\text{for}} = 2$ and $z_{\text{for}} = 5$ respectively and evolve passively thereafter (for $q_0 = 0.0$). The solid lines represent least-squares linear fits of slope γ . **(b)** As (a) but for $q_0 = 0.5$.

Figure 1 shows the K magnitude–redshift relation (Hubble diagram) for the BCGs in our sample. The scatter of the observed magnitudes around the no-evolution prediction is 0.30 mag. Assuming that the K -band light provides an estimate of the total stellar mass of the galaxies, this implies that BCGs at a given redshift have very similar masses in stars (within 30% *r.m.s.*). Moreover, the luminosity of the BCGs does not evolve strongly with redshift. This is shown more clearly on the top panel of Figure 2, where the no-evolution prediction has been subtracted from the data. For $q_0 = 0.0$ the observed magnitudes do not seem to evolve with redshift. For $q_0 = 0.5$ there is a hint of *negative* evolution: BCGs at high redshift tend to be marginally fainter than low redshift ones. If we parameterise the luminosity evolution as $L_K(z) = L_K(0) \times (1+z)^\gamma$, we get $\gamma = -0.06 \pm 0.3$ and -0.6 ± 0.3 , for $q_0 = 0.0$ and 0.5 respectively. Thus the BCGs show *no* or marginally *negative* luminosity evolution.

However the colours of these galaxies show the same evolution as the early-type cluster galaxies: they get progressively bluer with redshift at a rate which indicates that their stellar populations were formed at $z > 2$ and evolved passively thereafter. If the total stellar mass of the galaxies has remained constant, we would expect them to get progressively *brighter* with redshift, as the average ages of their stellar populations get younger. Since that brightening is not observed, the most likely explanation is that the total mass in stars in the BCGs has grown with time. We will now estimate the rate of this growth.

Using evolutionary population synthesis models (Bruzual & Charlot 1997) with a standard IMF we predict the expected luminosity evolution of a passively-evolving stellar population formed at a given redshift. That should represent the brightening of the stellar populations due to the decrease in average stellar age with redshift. The model predictions are plotted on Figure 1 (LE lines) for formation redshifts $z_{\text{for}} = 2$ and $z_{\text{for}} = 5$. These models produce a colour evolution compatible with the observations of early-type cluster galaxies. In Figure 2 (lower two panels) we have plotted the observed magnitudes after subtracting the luminosity evolution predictions. Since the models assume a constant stellar mass, the rate of change with redshift in the K magnitudes, after correcting for the expected brightening due to passive evolution, should be a direct measurement of the rate of change in stellar mass. Parameterising the evolution as $M_{\star}(z) = M_{\star}(0) \times (1+z)^{\gamma}$, we obtain the values of γ shown in Figure 2, which imply that the mass in stars of a typical BCG grew by a factor $\simeq 2$ if $q_0 = 0.0$ or $\simeq 4$ if $q_0 = 0.5$ from $z \simeq 1$ to $z \simeq 0$.

3. Galaxy formation and evolution models

The recent development of *semi-analytic techniques* has provided theorists with the tools to make predictions for the formation and evolution of galaxies, using physically motivated models set in the context of hierarchical structure formation in the universe. The properties of galaxies in these models are in broad agreement with the present day characteristics of galaxies, such as the distribution of luminosities, colours and morphologies and with the properties of galaxies at high redshift, including the faint galaxy counts, colours and redshift distributions. Full details of the models and these results can be found in Kauffmann et al. (1993, 1994) for the Munich models and Cole et al. (1994) and Baugh et al. (1996, 1997) for the Durham models. See also the contribution by Frenk in this volume. In these models, there are three different ways in which the stellar masses of the brightest galaxies in clusters can grow: (1) merging of satellite galaxies that sink to the center of the halo through dynamical friction; (2) quiescent star formation as a result of gas cooling from the surrounding hot halo medium; and (3) “bursts” of star formation associated with the merging of a massive satellite.

4. Discussion

In figures 3 and 4 we illustrate how $z = 0$ BCGs are predicted to evolve by the semi-analytic models. One unresolved problem in these models is that the colours and absolute magnitudes of central cluster galaxies are predicted to be

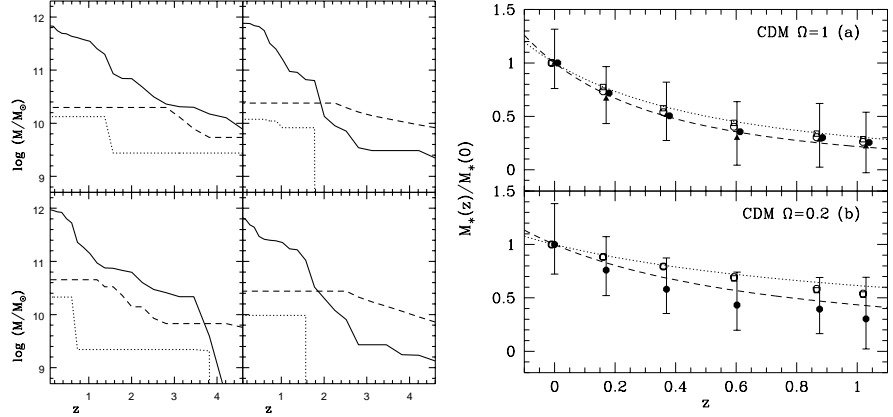


Figure 3. **(Left)** The build up in stellar mass of the largest progenitor in four example BCGs. The four panels represent independent Monte Carlo realizations of the formation of a BCG in a halo of circular velocity 1000 km s^{-1} . The solid lines show the accumulation of stellar mass from merging events, the dashed lines show the mass contributed by stars forming from gas cooling from the surrounding hot halo medium, and the dotted lines show the mass contributed by star formation bursts associated with major mergers. A Cold Dark Matter cosmology with critical density was assumed.

Figure 4. **(Right)** The average stellar mass of BCGs in halos of circular velocity 1000 km s^{-1} , normalised to the average BCG mass at redshift zero. **(a)** Predictions for a Cold Dark Matter universe with the critical density. **(b)** Predictions for an open universe. The density fluctuations in each case are normalised to reproduce the abundance of rich clusters. The open symbols show Durham models for isothermal halos (circles) and for halos with Navarro, Frenk & White (1996) density profiles (squares). The filled symbols show the Munich models; for the case of the filled circles, no visible stars form in the cooling flows of halos with circular velocities greater than 500 km s^{-1} . The filled triangles are for a model in which stars do form in massive cooling flows. The curves show the trends in stellar mass deduced in Section 2; the dotted curve corresponds to $z_{for} = 5$ and the dashed curve to $z_{for} = 2$. The error bars shown are representative of the scatter found in all the models ($\simeq 30$ percent, i.e., very close to the observed one).

too blue and too bright if all gas in the central cooling flows of massive clusters turns into stars with a normal IMF. The Munich models adopt a somewhat *ad hoc* fix by simply switching off star formation in cooling flows once the circular velocity of a halo grows larger than 500 km s^{-1} (this value was chosen so that the models produced a good fit to the bright end of the Virgo cluster luminosity function). Figure 3 shows that star formation from bursts and cooling gas then only account for a few percent of the final mass of the BCG. The rest comes from accreted galaxies.

The observational selection picks out *the richest clusters* at each redshift. We mimic this selection by calculating the masses of BCGs in halos of *fixed circular velocity* as a function of redshift. This means we are selecting rarer objects with increasing redshift. In Figure 4 we compare both the Durham and the Munich models with the observations. Note that different assumptions about the dark halo profiles or the formation of stars in cooling flows make very little difference to the predictions for the *relative change* in the masses of BCGs from $z = 0$ to 1. This is because the crucial parameter controlling this change is the *time since the Big Bang*. High redshift clusters have less massive BCGs because there has been less time for these galaxies to assemble as a result of merging or gas accretion.

The agreement between the models and the observations in both the rate of growth of the stellar mass and the scatter is remarkable: both models agree well with the data when the appropriate value of q_0 is used in the analysis. It is thus not possible to make statements about a preferred cosmology.

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